# NAVAL POSTGRADUATE SCHOOL

## Monterey, California

# THESIS

UNDERWATER GRAVITY SURVEY
OF
NORTHERN MONTEREY BAY

by

Brian Sullivan Cronyn

Thesis Advisors: Robert S. Andrews
J. J. von Schwind



March 1973

*Approved for public release; distribution unlimited.*

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Underwater Gravity Survey

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Northern Monterey Bay

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Brian Sullivan Cronyn
Lieutenant, United States Navy
B.S., United States Naval Academy, 1966

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

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# ABSTRACT

Eighty underwater gravity measurements were made in northern Monterey Bay in water depths from 38 feet to 456 feet with a Lacoste and Romberg Model H underwater gravity meter. In addition, seven shoreline stations were occupied just above the swash zone with a Lacoste and Romberg Model G land gravity meter.

A complete Bouguer anomaly map was drawn and tied in with the previous land surveys and with one (a joint investigation) covering the southern half of the bay.

The isolines of the complete Bouguer anomaly indicate the relative vertical position of the basement complex Santa Lucia granite and the overlying sedimentary strata of the Purisma and Monterey Formations. Analysis gives evidence of a basement complex ridge in the north bay. A two-dimensional model of the depth to basement along a representativ transect shows further evidence of the ridge. New evidence for an extended Monterey Canyon fault is presented.

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## ACKNOWLEDGEMENTS

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# I. INTRODUCTION

## A. OBJECTIVE

This survey was undertaken to obtain gravity data in the shallow water environment of northern Monterey Bay, an area where shipborne sea-surface gravimetry would be too unwieldy if not impossible. Bottom gravimetry is more feasible in shallow water and yields greater accuracy because the measurements are made on the bottom, a relatively stable platform.

The Monterey Bay area of California has seen much land gravity work, but little sea surface gravimetry and no bottom gravimetry. The main objective was to collect data in an essentially unsurveyed area and to reduce that data to the complete Bouguer anomaly in order to tie the data in with the previously surveyed land stations. In addition, an analysis of the contours of the complete Bouguer anomaly (CBA) was to be performed in order to infer the geological substructure of northern Monterey Bay.

## B. AREA DESCRIPTION

The survey was conducted in northern Monterey Bay in an area of approximately 120 sq n miles (Fig. 1). This area, roughly square in shape, is bounded by the Monterey and Soquel Canyons on the south, the breakerline from Moss Landing in the southeast to Natural Bridges

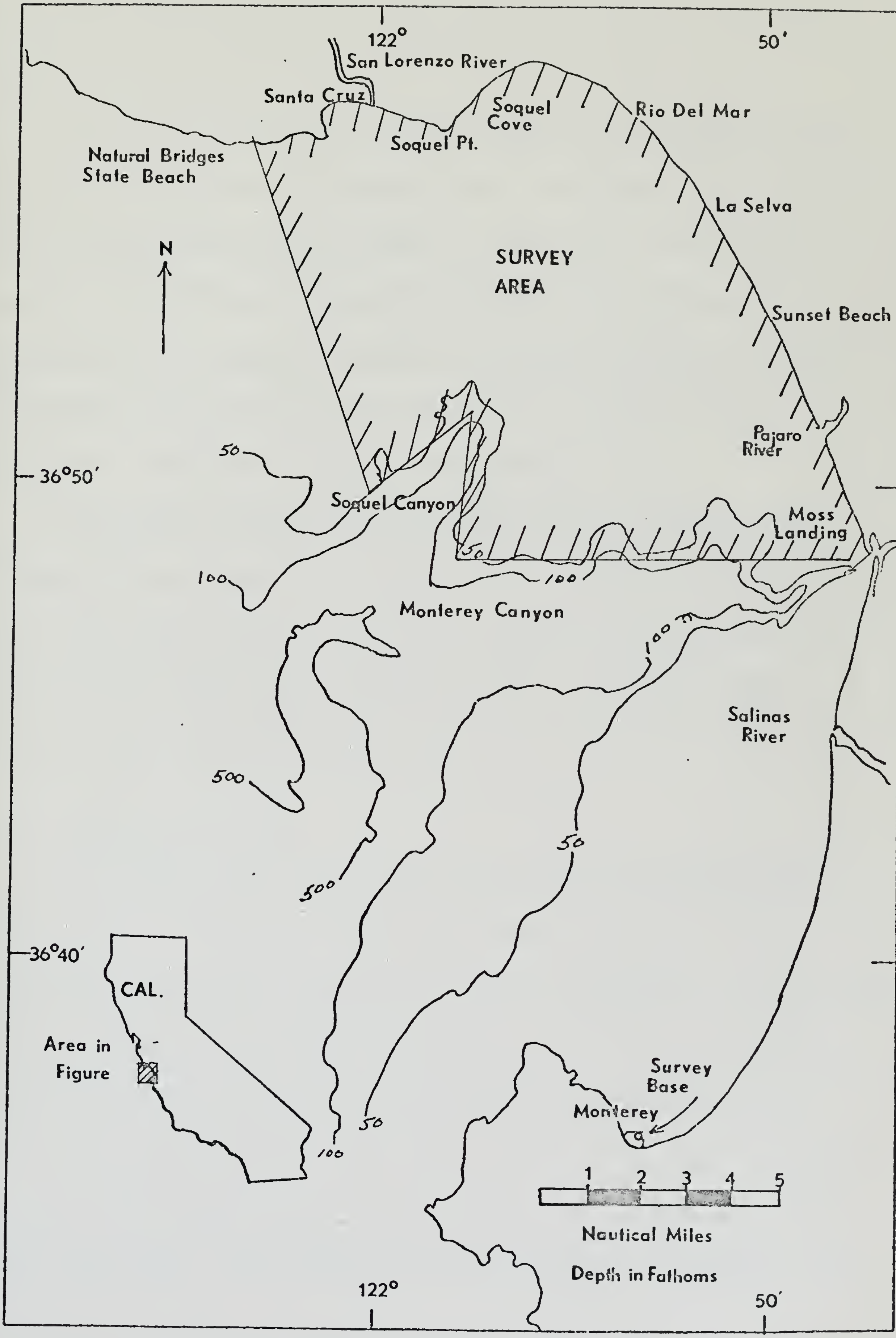



Fig. 1 Location of the survey area.

State Beach west of Santa Cruz, then south and east to the northwestern edge of Soquel Canyon.

Because of the presence of Monterey Canyon, the bathymetry of the area has been intensively investigated (Martin and Emery, 1967; Greene, 1970). Northern Monterey Bay exhibits a gentle bottom slope tending towards the very steep gradients of Soquel and Monterey Canyons. A general slope of 40 ft/n mile is observed with gentler slopes in the northwestern and central sectors of the survey area. The slopes steepen towards the south as the canyons are approached.

The Monterey Submarine Canyon emanates from directly offshore of Moss Landing and reaches a depth of 3,600 ft immediately southwest of the survey area. Soquel Canyon joins Monterey Canyon in the southwestern corner of the area at a depth of 3,200 ft. Slopes of 1,200 ft/n mile are common along the canyon walls.

## C. REGIONAL GEOLOGY

The geology of the area has been intensively investigated (Hart, 1966; and State of California Department of Water Resources, 1970). The oldest known rocks in the region are the Pre-Cretaceous metamorphosed marine sediments of the Paleozoic Sur Series. The Santa Lucia granites intruded into the Sur Series during Late Cretaceous times and comprise the basic basement complex of the region. The granite and Sur Series are peculiar to the Salinian Block, an area between the San Andreas and Sur Naciemento faults. The basement complex outcrops to the south in the

Santa Lucia Mountains and the Monterey Peninsula, to the west in the Gabilan Mountains, and to the north in the Santa Cruz Mountains.

During Miocene times the Monterey Formation of siliceous shale was deposited along with sea floor sediments and basal sand. The Purisma Formation of Pliocene sedimentary siltstone and sandstone is in evidence in the Santa Cruz Mountains and has been dredged from the slopes of Monterey Canyon. The southern bay and the Monterey Peninsula were probably above sea level at this time.

The Paso Robles Formation of Late Pliocene to Early Pleistocene sand, gravel, and clay was laid down in the south by river depositions on flood plains. Aromas Red Sands of similar river origin were then laid down over the entire bay region during the Pleistocene. Pleistocene and recent non-marine formations ring the bay at the present time and the shoreline is characterized by recent sand dunes overlying alluvium and terrace which in turn rest on the Aromas Red Sand.

The bay and shoreline evidence little in the way of rock outcropping with the exception of the Santa Lucia granite on the Monterey Peninsula, an area offshore of the Monterey Peninsula to the northwest, an outcropping of the Miocene Monterey Shale in the extreme southeastern sector of the bay, and Pliocene sedimentary strata and basement complex granite near Santa Cruz.

In the bay itself, sand covers the bottom until green mud predominates as the canyons are approached. Dredgings of the canyons reveal the presence of granite, sedimentary strata, and some metamorphics on

the south wall of Monterey Canyon, but only upper Pliocene sedimentary strata of the Purisma Formation north of the canyon axis (Martin and Emery, 1967). This sedimentary strata, along with possibly the Monterey Formation, forms the basic density contrast with the more dense granite of the basement complex.

Sediments presently reach Monterey Bay by littoral drift and transport via river drainage. The Salinas River is the main river emptying into the bay with the Pajaro and San Lorenzo Rivers contributing sediment to a lesser degree.

Major structural features of the bay include a buried ancestral canyon cut into the erosion surface at Moss Landing (Starke and Howard, 1968), the Monterey Graben to the west of the survey area (Martin and Emery, 1967), the Tularcitos and Gabilan Faults which traverse the south bay in a northwesterly direction (Greene, 1970), and the Monterey and Soquel Submarine Canyons.

## D. PREVIOUS WORK

Most of the previous marine geological explorations have centered on the Monterey Canyon. The canyon was first noted by the U.S. Coast and Geodetic Survey in the 1850's and both sporadic and intensive investigation has followed. Notable work concerning the Monterey Canyon has been done by Shepard and Emery (1941), Shepard (1948), Martin (1964), and by Martin and Emery (1967). In addition, much physical oceanographic research has been done by the Naval Postgraduate School (NPS).

Starke and Howard (1968) integrated gravity measurements and oil drilling data to suggest the existence of a buried submarine canyon at Moss Landing. Greene (1970) did extensive work in the bay and is, as of this writing, preparing for publication a study of the north bay.

On land, Sieck (1964) and Fairborn (1963) have compiled a complete Bouguer anomaly (CBA) map of the Monterey-Salinas area and the northern Salinas Valley, respectively. A preliminary gravity map of the land areas bordering on the north bay was prepared by Clark and Rietman (1970), while Bishop and Chapman (1967) combined all previous gravity work into a gravity map of the Santa Cruz sheet.

# II. SURVEY METHODS

## A. SURVEY EQUIPMENT

A Lacoste and Romberg underwater gravity meter, Model H, was used throughout the oceanographic part of the survey. Under optimum conditions the accuracy of underwater meters approaches that of land meters. Accuracy under good conditions is within 0.02 milligals (mgal) and remains better than 0.1 mgal under extreme conditions of adverse weather and soft bottoms.

The design of the meter itself is similar to Lacoste and Romberg land meters and has a 7,000 mgal range (Fig. 2). Waterproof casing and remote actuation and control (Fig. 3) of the meter functions permit the taking of accurate gravity measurements to a depth of 904 m with a modified system (Beyer, von Huene, McCulloh, and Lovett, 1966).

Within the meter, a mass at the end of a spring is balanced such that any small variation in gravity will move an attached beam slightly. The principle of the zero-length spring is used to effectively isolate elongation of the spring to that caused by a change in gravity felt by the mass. This is accomplished by pre-winding opposing tension into the spring to counteract the weight of the beam in the zero position. Angular change of beam and spring position resulting from gravity variations is nulled by a remotely operated adjusting screw.

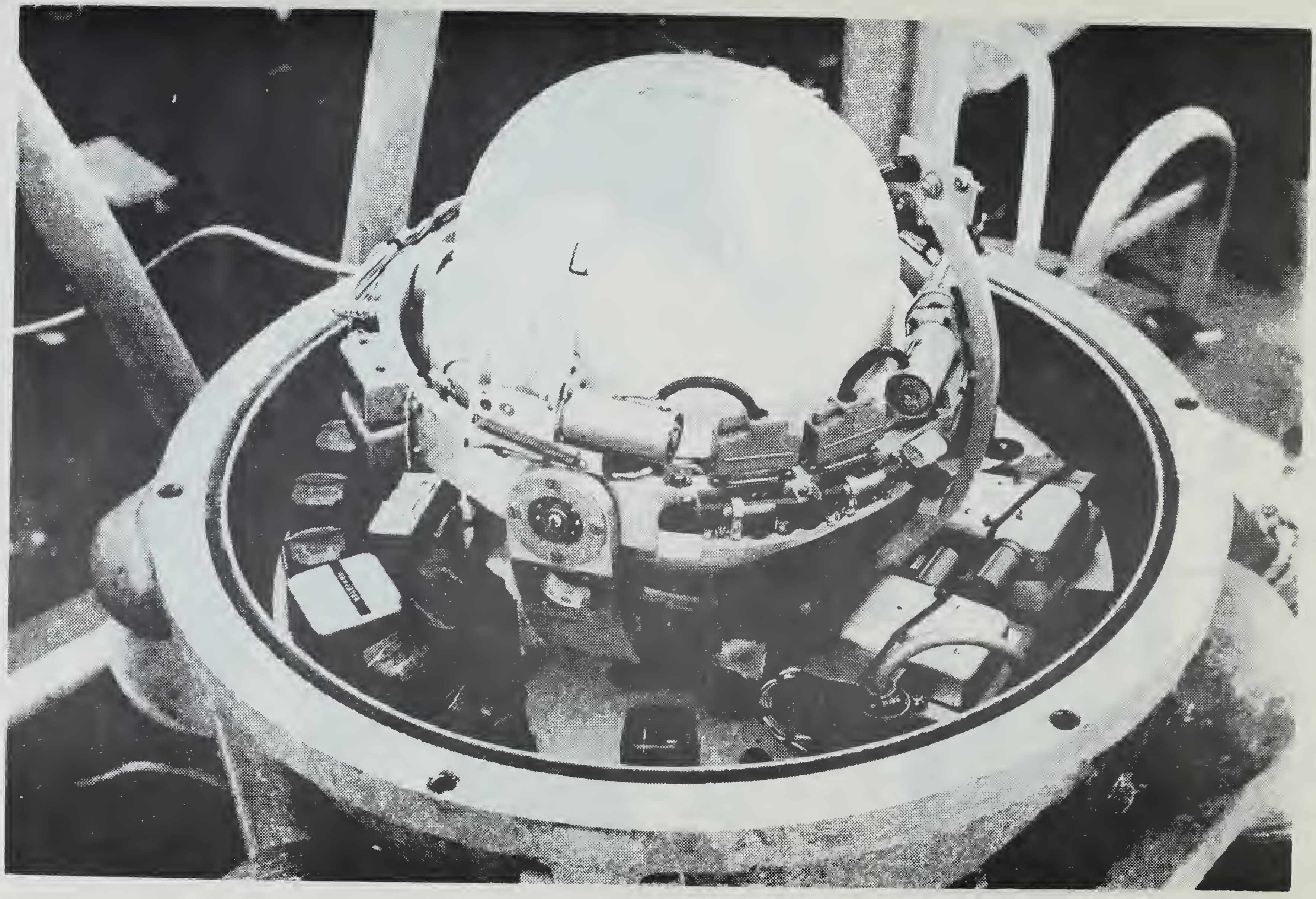


Fig. 2. Lacoste and Romberg Model H gravimeter with waterproof casing removed

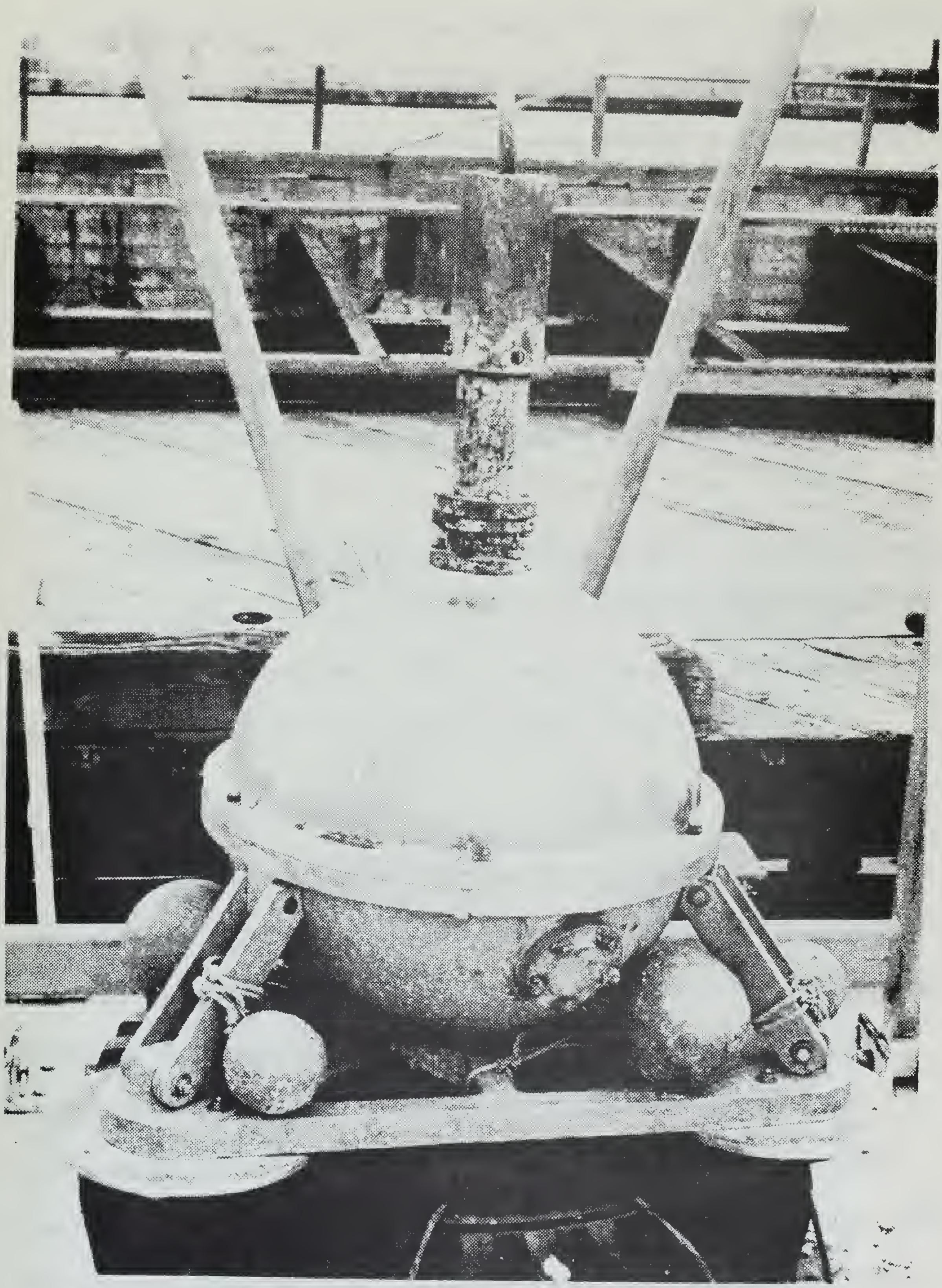


Fig. 3. Lacoste and Romberg Model H gravimeter fully sealed.

Remote operation of the meter through the control box includes modes for clamping and unclamping the mass, high and normal speed leveling, heating, nulling of the mass position, remote display of gravity counter and depth sensor counter units, and flood and tilt indications. Normal leveling is possible up to 15° of actual bottom tilt. The circuitry from meter to control box is routed through a conductor cable (casing grounded) which is used for raising and lowering the meter. A standard marine motor and hydraulic system are used for positioning an A-frame and for operating the winch.

All equipment was temporarily installed on the R/V ACANIA, research vessel of the Naval Postgraduate School. In addition,a Lacoste and Romberg land gravity meter, Model G, was utilized for tying in selected land stations with the oceanographic portion of the survey.

## B. PRELIMINARY WORK

The Lacoste and Romberg gravimeter, control box, and associated electronic and heavy equipment were obtained on loan from the Naval Oceanographic Office. The motor, winch, and A-frame were temporarily bolted to the aftmost portion of the R/V ACANIA's top deck (Fig. 4). Divers were utilized to examine the bottom immediately below the R/V ACANIA's mooring in Monterey Harbor, the survey's working base station. A flat sand bottom, free of all obstructions was observed. The divers were also used to observe and monitor meter lowering, setdown, cable laydown, and possible meter drag under brisk wind conditions in the bay. No complications were observed.

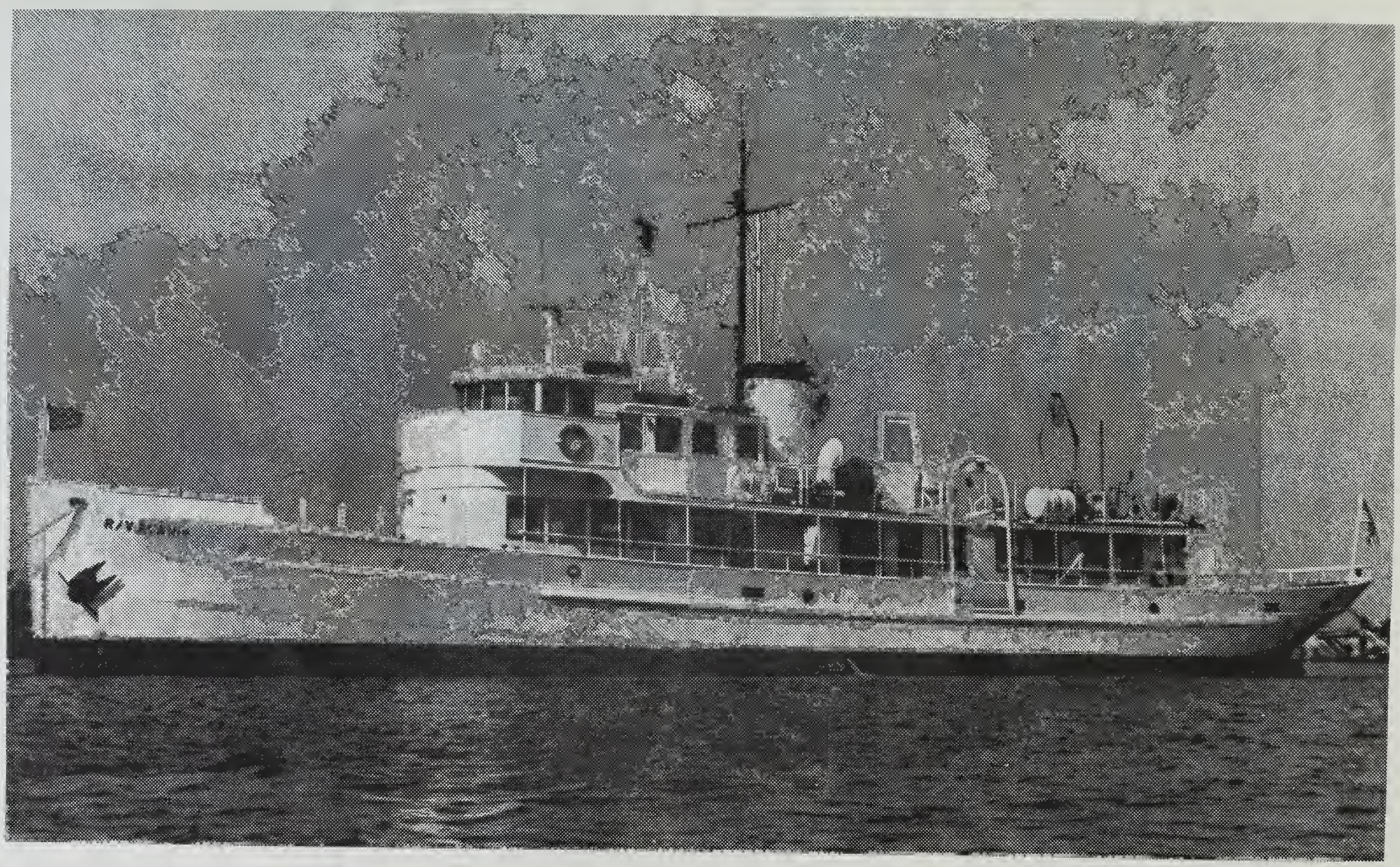


Fig. 4. R/V ACANIA with survey equipment installed aft .

The survey grid was established to investigate most thoroughly close inshore areas where sea surface gravimetry was impractical. Secondarily, areas adjacent to the submarine canyons were to be investigated closely in order to infer the geological history and structure of the submarine canyons. To this end a 1 n mile grid was used in these particular areas of interest. For the interior region, a 1 n mile latitudinal by 2 n mile longitudinal grid was initially established (Fig. 5).

## C. SURVEY OPERATIONS

Each day survey operations started with a gravity measurement at the survey's working base station. The meter was then raised and secured as the R/V ACANIA made directly to the first station of the day. The ship's master had initial navigational responsibility. When almost on station, the ship was slowed and the meter was lowered into the water. Once on station the ship was headed into the wind and the pressure sensor depth at the surface was taken. A navigational fix was then taken by one of the survey team members as the meter was lowered to the bottom. Meter lowering averaged 150 ft/min. Bottom arrival was determined by monitoring depth counter units. High speed leveling was initiated as pressure sensor depth counter units and a fathometer reading were recorded. After the meter was leveled, the mass was unclamped and a reading was taken. After obtaining a satisfactory reading the mass was clamped and the meter raised and lashed to the A-frame. Once the meter cleared the water the R/V ACANIA made best speed to the next station. A maximum of four to five stations per hour could be occupied under conditions of calm to light

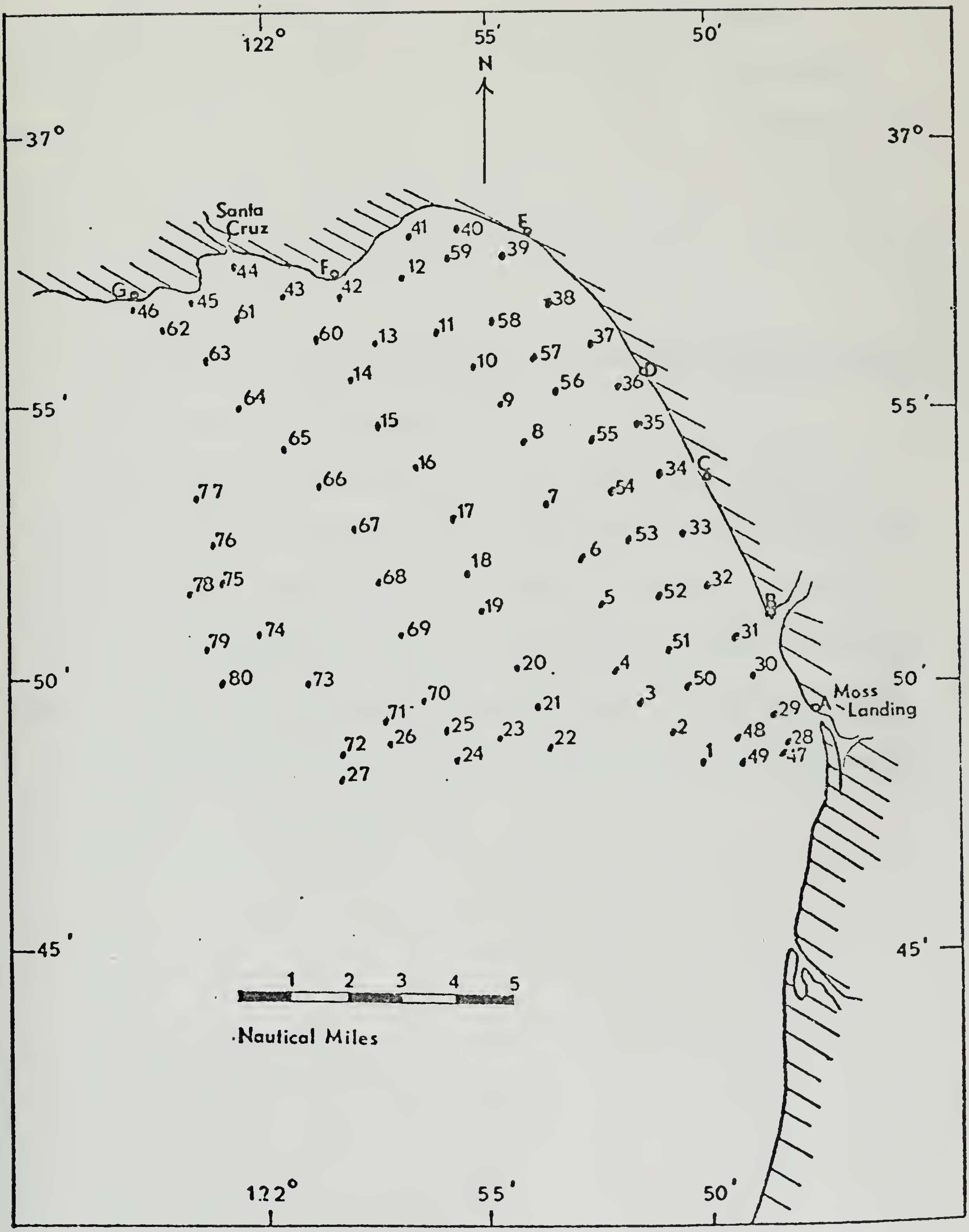



Fig. 5. Station grid.

seas at intermediate depth (10 to 30 fathoms). Longest time per station was observed in shallow water stations with a moderate swell running. Obtaining a satisfactory reading under these conditions was difficult because of the periodic oscillations induced by the swell in the meter reading. On the average, a reading was obtained within 2 - 4 min of the meter's reaching bottom.

Navigational procedures utilized were visual bearings, radar ranges, and fathometer readings where applicable.

Station keeping involved heading into the wind and/or prevailing swell and maintaining station by monitoring visual bearings and maneuvering as necessary. Cable was let out to sufficient length to assure no tension would be placed on the cable due to the ship's motion. No station keeping problems were encountered during the survey. After occupation of a series of stations, a reading was once again taken at the mooring base station so as to determine meter drift.

# III. DATA REDUCTION

## A. OBSERVED GRAVITY

A working base station (R/V ACANIA's mooring, Monterey Harbor) was tied in with the world harbor gravity station WH-29 located at the end of the Coast Guard pier (Woollard and Rose, 1963) by repeated occupations. At these base stations (both WH-29 and the mooring station) gravity observations were corrected for earth tide, water tide, and meter drift. The latter was applied by linear interpolation as a function of time to station measurements.

The observed gravity was then reduced to that gravity which would be measured on a mathematically-generated spheroid fitted as closely as possible to the geoid. The corrections which follow account for latitudinal, elevation, tidal, and topographic variations in the gravity experienced at a given point on the earth. After these variations have been eliminated, local, near-surface density variations will have been isolated as the cause of local gravity variations.

## B. THEORETICAL GRAVITY

The influence of a station's latitude on a gravity measurement is a consequence of the fact that the earth is not perfectly spherical and that the component of centrifugal force opposing gravity diminishes from the equator to the poles. To mathematically approximate the true shape of the earth, a modified ellipsoid of revolution with bulging equator, flattened

poles, and depressions along the 45° latitudes is used. Gravity values as a function of latitudinal position on the modeled surface are expressed by:

$$g = g_e\,(1 + C_1 \sin^2 L + C_2 \sin^2 2L) \qquad [1]$$

where $g_e$ is the value of gravity at the equator at 180° longitude, $C_1$ and $C_2$ are constants which incorporate pendulum gravity measurements into a best fit of the ellipsoid to the geoid, and L is the station latitude.

The 1930 International Constants (Dobrin, 1960) were used for this survey. Upon substitution, the theoretical gravity ($g_t$) in milligals at any latitude is expressed by:

$$g_t = 978049\,(1 + 0.0052884 \sin^2 L - 0.0000059 \sin^2 2L) \qquad [2]$$

Double precision arithmetic was used in the computer program for this calculation.

## C. TIDAL CORRECTION

Earth tide corrections must be added to observed gravity to eliminate the effects of the gravitational pull of the sun and moon on the non-rigid earth. These earth tides are easily calculated from orbital predictions of the movement of the sun and moon with respect to the earth. The United States Geological Survey (USGS) earth tide program was used in this respect. The tidal correction is a small one (a complete tidal cycle emcompassing a maximum range of only 0.3 mgal), but it is important in determining meter drift.

## D. DRIFT CORRECTION

The gravimeter has an acceptable drift rate of 1 mgal/month (Lacoste and Romberg, 1970). Drift was closely monitored throughout the survey, despite long transit times. The maximum drift rate observed was 0.018 mgal/hour, based on periodic occupation of the base station in Monterey Harbor.

## E. FREE AIR CORRECTION

The free air correction repositions the gravity station to mean sea level (the approximate reference spheroid). This repositioning does not take into account the existence of any crustal or oceanic matter existing between actual station depth and mean sea level. The commonly used free air correction factor (FAC) of 0.09406 mgal/ft was used. Mean sea level, for purposes of this survey, was taken as mean sea level for 1971, as determined at the NPS tide gauge at Monterey Wharf No. 2. In bottom gravity work the free air correction is negative since the station is repositioned further away from the center of mass of the earth.

## F. BOUGUER CORRECTION

The Bouguer correction compensates for the mass neglected in repositioning the station through the free air correction. In bottom gravimetry a double Bouguer correction is used because of the existence of water above the meter.

The first Bouguer correction ($BC_1$) is given by:

$$BC_1 = 2\pi G \rho_{cr} Z_1 \qquad [3]$$

where G is the universal gravitational constant, $\rho_{cr}$ is $2.67 g/cm^3$, the mean density of crustal rock, $Z_1$ is the distance to mean sea level, the observed depth minus the water tide level. This correction fills the distance from actual station depth to mean sea level with a uniform infinite plate of mean crustal density. The correction is a positive one for underwater work.

The second Bouguer correction ($BC_2$) is given by:

$$BC_2 = 2\pi G \rho_{sw} Z_2 \qquad [4]$$

where $\rho_{sw}$ is the average density of sea water, $1.03 \ g/cm^3$, and $Z_2$ is the observed depth of the station (distance between sea surface and bottom at time of readings). This term is peculiar to bottom gravimetry work. In effect it removes the upward attraction of the water layer located immediately above the meter. Since this correction removes the oppositely directed attraction of water above the meter, it is also positive. The combined Bouguer correction for underwater stations can be expressed by the formula;

$$BC_1 + BC_2 = 2\pi G(\rho_{cr} Z_1 + \rho_{sw} Z_2) \qquad [5]$$

## G. TERRAIN CORRECTION

The terrain correction compensates for topographical irregularities above and below the station. The Bouguer correction assumed a smooth infinite plate. In actuality, deficiencies of mass below the station and excesses of mass above the station must be eliminated. All depressions of the earth's surface below a horizontal plane through the meter diminish

the value of observed gravity. All projections of the earth's surface above a horizontal plane through the meter diminish the value of observed gravity due to their oppositely directed attraction. In both cases a correction must be added to the value of observed gravity.

The terrain correction is generally applied through the use of templates and tables first devised by Hayford and Bowie (1912). In essence, the surrounding terrain is divided into a set of compartments formed by the combination of concentric circles, centered over the station and radial lines passing through the station. The average elevation within each compartment is computed and compared to station elevation to obtain a height differential. This height differential is then multiplied by a factor which relates the zone of the compartment, the height differential and an assumed density (2.67 g/cm$^3$) to the vertical gravitational contribution at the station.

The zones proceed outward from Zone A at an outer radius of 6.6 ft with two compartments to Zone O with outer radius of 546,793 ft (approximately 100 miles) and 28 compartments. Numbered zones from 18 to 1 proceed outward from Zone O to the antipodes of the station.

In general practice, terrain corrections are carried out to Zone O. For purposes of this survey USGS modified tables derived from Swick (1942) for use with underwater stations were used. (Modifications of Cassinis' (1937) table by Robbins and Oliver (1970) were used for Zone A for the seven land stations.) Zone A was neglected for underwater stations because there was no practical way of determining the terrain immediately around the meter. This introduces no large error, for the maximum

correction for a vertically infinite cliff immediately adjacent to the meter is only 0.1 mgal (Robbins and Oliver, 1970). In fact, most of the area immediately adjacent to the stations featured flat bathymetry. Because of the relatively few stations involved and the lack of good depth digitization, all terrain corrections were done by hand.

The use of standard tables for computing terrain corrections is complicated by the fact that they must be modified for underwater work. The standard tables assume air where depressions exist. In underwater work the density of water must be taken into account. This is done by using a proportionality constant of 0.615 when encountering a water component whose average bottom depth is less than that of the station:

$$\frac{\rho_{cr} - \rho_{sw}}{\rho_{cr}} = 0.615 \qquad [6]$$

This factor compensates for the actual attraction of the mass of water in the compartment.

In applying a double Bouguer correction, any solid material lying above the station depth, but below mean sea level, assumes an excess density. This is a result of subtracting the effect of water and adding a Bouguer plate to already existing crustal material. In essence, these compartments have been given an effective density $\rho_m$ of:

$$\rho_{cr_1} - \rho_{sw} + \rho_{cr_2} = \rho_m \qquad [7]$$

where $\rho_{sw}$ is the average density of sea water, $\rho_{cr_1}$ is the actual (but unknown) average crustal density in the compartment, $\rho_{cr_2}$ is the

assumed average crustal density (taken as 2.67 $g/cm^3$). For this investigation it was taken that $\rho_{cr_1} = \rho_{cr_2}$. In this case $\rho_m$ is an effective density of 4.31 $g/cm^3$.

For those compartments which are below mean sea level we must assume a negative contribution to the topographic correction corresponding to an excess density of 1.64 $g/cm^3$. For compartments which lie in part above mean sea level and in part below, the correction must be prorated according to the estimated fraction of the compartment occupied by each portion.

In practice, due to the relatively regular topography, the plate of excess mass is not of sufficient height to influence gravity to any significant extent at the station and is consequently neglected.

Terrain corrections, as mentioned earlier, are always positive and in this survey ranged from 5.33 mgal at Station 27 near the junction of the Monterey and Soquel Canyons to 1.93 mgal at Stations 34 and 55, remote from the canyons and the Santa Cruz Mountains.

## H. CURVATURE CORRECTION

The Bouguer correction assumes a flat earth projecting outward from the gravity station. This is a reasonable assumption for short distances, but is inaccurate for the greater distances involved when carrying terrain correction out to Zone O, a distance of 100 miles. The USGS curvature correction (in milligals) was used and is given by the expression:

$$CC = 0.0004462H - 3.282X\ 10^{-8}H^2 + 127X10^{-15}H^3 \qquad [8]$$

where H is the station elevation in feet above sea level. Since H is always negative for the bottom station, the curvature correction is negative and in actuality varied from -0.015 mgal at a depth of 40 ft to -0.214 mgal at a depth of 456 ft.

## I. GRAVITY ANOMALIES

A gravity anomaly exists when after application of the appropriate corrections to an observed reading there still exists a difference from theoretical gravity at the station. It is by analyzing the isolines of the anomaly values that local and regional gravity relationships may be observed and geological sub-structure inferred. Four types of anomalies are commonly used:

### 1. Free Air Anomaly

The free air anomaly (FAA) is that residual which exists after tidally corrected observed gravity has been modified by the free air correction and subtracted from the theoretical gravity. Thus, the free air anomaly is given by:

$$FAA = (g_o - FAC) - g_t \qquad [9]$$

where $g_o$ is the observed gravity (corrected for earth tides and meter drift) and $g_t$ is the theoretical gravity.

### 2. Mass-Adjusted Free Air Anomaly

A mass-adjusted free air anomaly (FAA') has been determined for purposes of making comparisons with sea-surface gravity readings. They should be approximately the same for any one location. Basically,

the station is repositioned at mean sea level. The mass adjusted free air anomaly is given by:

$$FAA' = g_o - g_t - FAC + BC_2 + 2\pi G \rho_{sw} Z_1 \qquad [10]$$

where the last term in this equation accounts for the downward attraction of the water for the meter repositioned at the reference spheroid.

3. Simple Bouguer Anomaly

The simple Bouguer anomaly (SBA) is determined by applying the Bouguer correction to the free air anomaly. This anomaly can be used to tie in data of local interest. In areas of uniform topography (the Gulf of Mexico) the simple Bouguer anomaly is the major basis of comparison. The SBA is given by the expression:

$$SBA = (g_o - FAC + BC_1 + BC_2) - g_t = (FAA + BC_1 + BC_2) \qquad [11]$$

4. Complete Bouguer Anomaly

When the data is further refined by eliminating the effects of irregular topography and the effects due to the curvature of the earth, the complete Bouguer anomaly (CBA) is obtained. The CBA is most commonly used to tie-in areas of regional interest. The CBA isolines should reflect near-surface variations of density and composition. The CBA is given by the relationship:

$$CBA = (g_o - FAC + BC_1 + BC_2 + TC - CC) - g_t = (SBA + TC - CC) \qquad [12]$$

J. ERROR ANALYSIS

The maximum possible error encountered is a sum of many probable error sources. The pressure sensor depth is estimated to be subject to a

maximum error of 0.5% of total depth. This would result in a maximum depth error of ±2.3 ft for a depth of 456 ft. This translates into a maximum computational error of 0.16 mgal in computing the CBA.

The inherent error in determining observed gravity with a Lacoste and Romberg Model H gravity meter is 0.10 mgal under the most adverse conditions. Another possible source of error was the reading error inherent in nulling the meter. Swell oscillation made reading difficult in shallow areas when swell was present. Maximum reading error was judged to be ±0.10 mgal.

The calculation of terrain correction introduced possible error through elevation estimation and bathymetry inaccuracy. A number of stations were calculated twice to determine variability in terrain corrections. An average of the highest 1/3 of the variations from previously determined terrain corrections was ±0.20 mgal.

An additional error of ±0.20 mgal may be assumed for elevation estimation bias by the author giving a total terrain correction error of ±0.40 mgal.

Navigational control was precise. Visual bearings and radar ranges were available throughout the survey with the exception of a few shoreward stations where fog inhibited good visual fixing. A maximum error of ±0.15 n mile positional area gives a maximum milligal error of ±0.21 mgal.

TABLE I

SOURCES OF ERROR

| | |
|---|---|
| DEPTH ERROR | $\pm 0.16$ mgal |
| METER ERROR | $\pm 0.10$ mgal |
| READING ERROR | $\pm 0.10$ mgal |
| TERRAIN ERROR | $\pm 0.40$ mgal |
| NAVIGATIONAL ERROR | $\pm 0.21$ mgal |
| TOTAL ERROR POSSIBLE | $\pm 0.97$ mgal |

## IV. DATA ANALYSIS

### A. GENERAL DISCUSSION

An analysis of the distribution of the complete Bouguer anomaly reflects the vertical displacement of the basement complex Santa Lucia granite with respect to the overlying sedimentary strata of the Purisma Formation and the Monterey Formation. In reducing the gravity observations to the complete Bouguer anomaly we have isolated this near-surface density contrast as the primary cause for an anomalous gravity distribution. The reduced data of the survey is tabulated in Table II with pertinent information included as Appendix A.

The depth to basement is ill-defined and irregular in the north bay. It is until only recently that seismic reflection profiling has indicated its depth north of Monterey Canyon. A jointly sponsored survey by the Naval Postgraduate School and the U.S. Geological Survey using a 160 kJ seismic reflection profiler was carried out in November of 1972. Previous explorations with 12 kJ equipment (Greene, 1970) failed to show the granite basement north of the canyon. Personal communication between the author and H. G. Greene of the USGS indicated good agreement between gravity data and the as yet unpublished 160 kJ seismic reflection data.

The distribution of the CBA values ties in well with trends established by Clark (1970) and Bishop and Chapman (1967). The isolines have been extended over land areas in conformity with their work (Fig. 6). Some offset was noted from the Pajaro River to Soquel Cove. This can be

TABLE II

REDUCED GRAVITY DATA

| STA | LATITUDE N | | LONGITUDE W | | DEPTH ft | FAA mgal | MFAA mgal | SBA mgal | CBA mgal |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 36 | 48.28 | 121 | 50.05 | 218.0 | -23.27 | -17.5 | -12.99 | -10.58 |
| 2 | 36 | 49.09 | 121 | 50.85 | 333.0 | -21.39 | -12.6 | -5.68 | -3.43 |
| 3 | 36 | 49.85 | 121 | 51.58 | 278.0 | -14.73 | -7.4 | -1.61 | 0.52 |
| 4 | 36 | 50.33 | 121 | 52.14 | 195.0 | -8.53 | -3.4 | 0.66 | 2.75 |
| 5 | 36 | 51.55 | 121 | 52.49 | 127.0 | -5.19 | -1.8 | 0.79 | 2.81 |
| 6 | 36 | 52.35 | 121 | 52.96 | 113.0 | -4.25 | -1.3 | 1.07 | 3.03 |
| 7 | 36 | 53.30 | 121 | 53.63 | 92.0 | -2.93 | -0.5 | 1.41 | 3.34 |
| 8 | 36 | 54.39 | 121 | 54.12 | 80.0 | -1.25 | 0.9 | 2.52 | 4.44 |
| 9 | 36 | 55.12 | 121 | 54.62 | 77.0 | 0.38 | 2.4 | 4.01 | 5.95 |
| 10 | 36 | 55.94 | 121 | 55.20 | 68.7 | 4.53 | 6.3 | 7.78 | 9.76 |
| 11 | 36 | 56.51 | 121 | 56.24 | 64.5 | 8.35 | 10.0 | 11.41 | 13.40 |
| 12 | 36 | 57.12 | 121 | 57.10 | 50.2 | 11.34 | 12.7 | 13.72 | 15.78 |
| 13 | 36 | 56.16 | 121 | 57.35 | 80.0 | 8.58 | 10.7 | 12.38 | 14.49 |
| 14 | 36 | 55.42 | 121 | 57.81 | 90.6 | 6.54 | 8.9 | 10.83 | 12.93 |
| 15 | 36 | 54.80 | 121 | 57.16 | 96.8 | 2.77 | 5.3 | 7.37 | 9.42 |
| 16 | 36 | 54.91 | 121 | 56.30 | 101.0 | -0.88 | 1.8 | 3.93 | 5.93 |
| 17 | 36 | 52.95 | 121 | 55.70 | 126.0 | -2.89 | 0.4 | 3.10 | 5.10 |
| 18 | 36 | 52.10 | 121 | 55.31 | 178.0 | -6.26 | -1.6 | 2.21 | 4.26 |
| 19 | 36 | 51.36 | 121 | 55.00 | 207.0 | -7.01 | -1.6 | 2.82 | 5.01 |
| 20 | 36 | 50.34 | 121 | 54.30 | 236.0 | -9.75 | -3.5 | 1.47 | 3.74 |
| 21 | 36 | 49.55 | 121 | 53.90 | 261.0 | -13.48 | -6.6 | -1.08 | 1.32 |
| 22 | 36 | 48.45 | 121 | 53.28 | 303.0 | -19.62 | -11.6 | -5.23 | -1.25 |
| 23 | 36 | 48.82 | 121 | 54.80 | 293.0 | -15.57 | -7.9 | -1.65 | 1.26 |
| 24 | 36 | 48.44 | 121 | 55.91 | 297.5 | -16.93 | -9.1 | -2.80 | 0.55 |
| 25 | 36 | 49.11 | 121 | 56.03 | 287.8 | -16.24 | -8.7 | -2.57 | 0.17 |
| 26 | 36 | 48.93 | 121 | 57.50 | 294.2 | -17.42 | -9.7 | -3.45 | -0.00 |
| 27 | 36 | 48.15 | 121 | 58.18 | 327.8 | -18.92 | -10.3 | -3.37 | 1.81 |
| 28 | 36 | 48.68 | 121 | 48.06 | 69.9 | -24.52 | -22.7 | -21.25 | -19.20 |
| 29 | 36 | 49.42 | 121 | 48.55 | 49.3 | -23.10 | -21.8 | -20.81 | -18.78 |
| 30 | 36 | 50.29 | 121 | 48.92 | 50.7 | -20.33 | -19.0 | -17.99 | -16.01 |

TABLE II (continued)

| STA | LATITUDE N | LONGITUDE W | DEPTH ft | FAA mgal | MFAA mgal | SBA mgal | CBA mgal |
|---|---|---|---|---|---|---|---|
| 31 | 36 51.10 | 121 49.46 | 49.0 | -16.60 | -15.3 | -14.36 | -12.39 |
| 32 | 36 52.09 | 121 49.98 | 51.4 | -14.93 | -13.6 | -12.60 | -10.66 |
| 33 | 36 52.90 | 121 50.50 | 48.3 | -10.86 | -9.6 | -8.69 | -6.75 |
| 34 | 36 53.86 | 121 50.96 | 44.0 | -6.09 | -5.0 | -4.13 | -2.22 |
| 35 | 36 54.70 | 121 51.55 | 44.2 | -3.87 | -2.7 | -1.92 | 0.02 |
| 36 | 36 55.48 | 121 52.22 | 43.0 | -1.75 | -0.7 | 0.15 | 2.11 |
| 37 | 36 56.26 | 121 52.72 | 44.2 | -0.14 | 1.0 | 1.80 | 3.81 |
| 38 | 36 57.03 | 121 53.72 | 40.8 | 2.60 | 3.6 | 4.37 | 6.42 |
| 39 | 36 57.60 | 121 54.59 | 38.5 | 5.40 | 6.4 | 7.05 | 9.15 |
| 40 | 36 58.08 | 121 55.65 | 34.1 | 10.93 | 11.8 | 12.38 | 14.50 |
| 41 | 36 57.77 | 121 56.70 | 40.0 | 12.31 | 13.3 | 14.03 | 16.10 |
| 42 | 36 56.79 | 121 58.25 | 53.8 | 12.49 | 13.9 | 14.87 | 16.94 |
| 43 | 36 56.80 | 121 59.42 | 50.8 | 14.33 | 15.6 | 16.57 | 18.65 |
| 44 | 36 57.36 | 122 0.42 | 40.6 | 17.45 | 18.5 | 19.20 | 21.29 |
| 45 | 36 56.71 | 122 1.43 | 58.6 | 17.85 | 19.3 | 20.45 | 22.53 |
| 46 | 36 56.63 | 122 3.31 | 62.6 | 22.73 | 24.3 | 25.54 | 27.70 |
| 47 | 36 48.64 | 121 48.06 | 81.6 | -25.13 | -23.0 | -21.37 | -19.33 |
| 48 | 36 48.90 | 121 49.29 | 118.5 | -20.59 | -17.5 | -15.06 | -12.93 |
| 49 | 36 48.29 | 121 49.17 | 139.0 | -21.49 | -17.8 | -14.98 | -12.60 |
| 50 | 36 50.05 | 121 50.20 | 123.2 | -16.38 | -13.2 | -10.52 | -8.42 |
| 51 | 36 50.76 | 121 50.80 | 108.2 | -10.61 | -7.8 | -5.47 | -3.35 |
| 52 | 36 51.72 | 121 51.00 | 77.0 | -8.21 | -6.2 | -4.56 | -2.56 |
| 53 | 36 52.71 | 121 51.49 | 71.3 | -6.66 | -4.8 | -3.29 | -1.38 |
| 54 | 36 53.50 | 121 52.09 | 69.2 | -3.61 | -1.8 | -0.35 | 1.56 |
| 55 | 36 54.35 | 121 52.78 | 64.6 | -1.34 | 0.3 | 1.69 | 3.59 |
| 56 | 36 55.30 | 121 53.27 | 59.0 | -0.44 | 1.1 | 2.31 | 4.24 |
| 57 | 36 56.06 | 121 53.88 | 55.0 | 1.53 | 3.0 | 4.08 | 6.05 |
| 58 | 36 56.74 | 121 54.82 | 52.9 | 5.46 | 6.8 | 7.90 | 9.93 |
| 59 | 36 57.40 | 121 55.83 | 47.2 | 9.03 | 10.2 | 11.18 | 13.23 |
| 60 | 36 56.18 | 121 58.49 | 78.1 | 10.05 | 12.1 | 13.65 | 15.72 |
| 61 | 36 56.28 | 122 0.19 | 69.8 | 14.20 | 16.0 | 17.41 | 19.50 |
| 62 | 36 56.08 | 122 2.45 | 65.5 | 17.78 | 19.5 | 20.77 | 22.94 |
| 63 | 36 55.56 | 122 1.20 | 91.1 | 11.89 | 14.3 | 16.07 | 18.26 |
| 64 | 36 54.96 | 122 0.38 | 113,5 | 6.94 | 9.9 | 12.18 | 14.31 |
| 65 | 36 54.20 | 121 59.47 | 117.3 | 3.46 | 6.5 | 8.87 | 11.04 |

TABLE II (continued)

| STA | LATITUDE N | | LONGITUDE W | | DEPTH ft | FAA mgal | MFAA mgal | SBA mgal | CBA mgal |
|---|---|---|---|---|---|---|---|---|---|
| 66 | 36 | 53.44 | 121 | 58.72 | 127.9 | -0.88 | 2.4 | 5.03 | 7.24 |
| 67 | 36 | 52.54 | 121 | 58.20 | 191.0 | -8.02 | -3.0 | 0.86 | 3.13 |
| 68 | 36 | 51.66 | 121 | 57.89 | 326.0 | -15.04 | -6.5 | 0.22 | 2.61 |
| 69 | 36 | 50.78 | 121 | 57.09 | 456.0 | -21.59 | -9.6 | -0.20 | 2.37 |
| 70 | 36 | 49.67 | 121 | 56.50 | 282.0 | -13.35 | -6.0 | -0.18 | 2.54 |
| 71 | 36 | 49.28 | 121 | 57.53 | 296.0 | -16.56 | -8.8 | -2.73 | 0.68 |
| 72 | 36 | 48.63 | 121 | 58.19 | 306.0 | -18.20 | -10.2 | -3.90 | 0.87 |
| 73 | 36 | 50.00 | 121 | 59.03 | 356.0 | -20.23 | -10.9 | -3.55 | 1.10 |
| 74 | 36 | 50.90 | 122 | 0.03 | 279.0 | -18.90 | -11.6 | -5.85 | -3.19 |
| 75 | 36 | 51.75 | 122 | 0.72 | 242.1 | -17.60 | -11.3 | -6.29 | -3.84 |
| 76 | 36 | 52.32 | 122 | 1.04 | 212.0 | -13.17 | -7.6 | -3.27 | -0.92 |
| 77 | 36 | 53.18 | 122 | 1.45 | 176.5 | -5.64 | -1.0 | 2.59 | 4.93 |
| 78 | 36 | 51.65 | 122 | 1.90 | 258.8 | -18.57 | -11.8 | -6.43 | -4.03 |
| 79 | 36 | 50.62 | 122 | 1.11 | 289.0 | -19.03 | -11.4 | -5.46 | -2.82 |
| 80 | 36 | 49.96 | 122 | 0.68 | 299.0 | -16.98 | -9.1 | -2.92 | 0.31 |
| A | 36 | 48.50 | 121 | 47.65 | 0.0 | -24.53 | -24.4 | -24.15 | -22.10 |
| B | 36 | 51.20 | 121 | 48.59 | 0.0 | -20.12 | -20.1 | -19.92 | -18.03 |
| C | 36 | 53.79 | 121 | 50.28 | 0.0 | -8.25 | -8.2 | -7.89 | -5.69 |
| D | 36 | 55.89 | 121 | 51.64 | 0.0 | -1.92 | -1.9 | -1.67 | 0.39 |
| E | 36 | 58.09 | 121 | 54.30 | 0.0 | 6.56 | 6.6 | 6.84 | 8.95 |
| F | 36 | 57.27 | 121 | 58.50 | 0.0 | 14.26 | 14.4 | 14.68 | 16.98 |
| G | 36 | 56.94 | 122 | 3.33 | 0.0 | 26.66 | 26.7 | 26.83 | 29.20 |

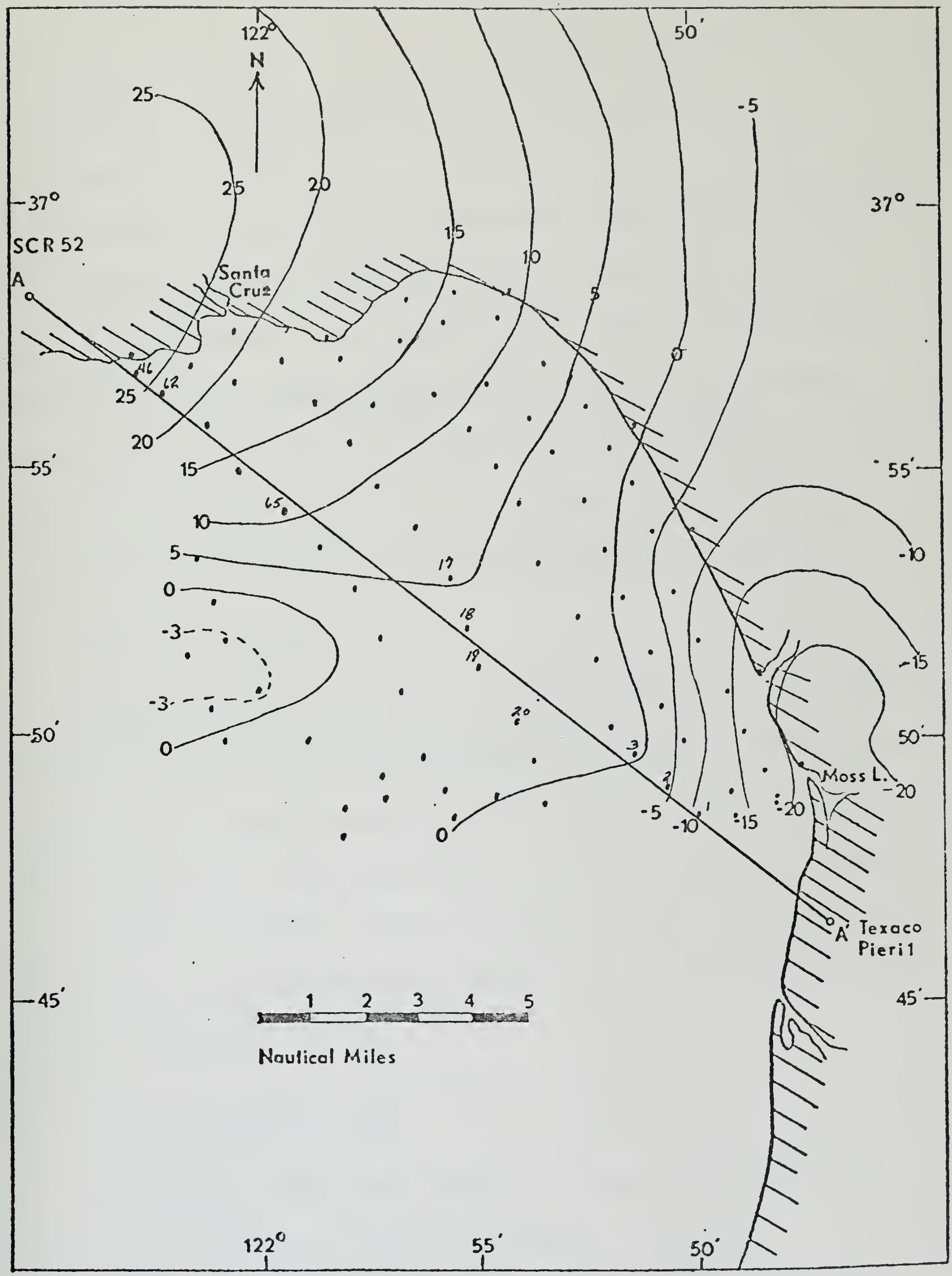



Fig. 6. CBA distribution for northern Monterey Bay.

attributed to a paucity of previously established gravity stations near the shoreline. The seven land stations of the present survey were used in extending the contours.

An analysis of gravity data alone cannot satisfy criteria for uniqueness in defining subsurface structure. Many possible interpretations could be consistent with given distribution of the CBA. To fully utilize gravity data, local geological observations, well data, grab samples, magnetics, and seismic data are incorporated in the analysis in an attempt to find a unique model of the subsurface structure. All useful available geophysical and geological data has been incorporated in this analysis.

## B. SANTA CRUZ HIGH

An initial examination of the distribution of the CBA reveals a general downward trending of the basement complex in the bay from northwest to southeast. The basement complex outcrops onshore north of Natural Bridges State Beach. Well data shows a depth to basement onshore near Moss Landing on the order of 3,255 ft (Fairborn, 1963). The high valued CBA isolines in the northwest trace the gradual downward trending of the basement complex.

## C. MONTEREY GRABEN LOW

The gradient of the gravity isolines increases to the south, indicating a somewhat steeper slope to the granite. An area to the northwest of Soquel Canyon shows the initial lines of a low forming. These few lines may indicate the eastern reaches of the Monterey Graben (proposed

by Martin and Emery (1967)). Dredgings of the Monterey Canyon north wall and Soquel Canyon in this area reveal only sedimentary strata of the Purisma Formation although granite has been dredged from the immediately opposite south wall (Martin, 1964). The eastern edge of Soquel Canyon is typified by an area of near zero positive CBA values. Using an easterly declining regional trend one may assume that here, too, the granite trends downward to the low area to the northwest.

## D. MOSS LANDING

The granite dips sharply downward as Moss Landing is approached from the northwest. Closely spaced isolines indicate the steepened gradient. Neither the distribution of the CBA nor the isolines of gradicule-determined residual gravity (Dobrin, 1960) give indications of the buried submarine canyon. Otherwise, the isolines tie-in well with previously determined landward trends.

## E. INTERIOR RIDGE

The interior of the area shows strong evidence of a basement ridge. The 5-mgal contour and the values at Stations 17, 18, 19, and 20 show a general upward trending of the basement complex. The general downward trend of the basement complex from northwest to southeast is modified as a strong indication of a ridge of minor local extent is noted. The feature appears to reach its high point near Station 19.

F. GRAVITY PROFILE A-A': DISCUSSION AND ANALYSIS

A gravity profile, section A-A', from Bishop and Chapman's (1967) Station SCR 52 to the Texaco Pieri 1 well (Fig. 6), a distance of 19.5 n mile (36 km) was prepared. The profile was constructed using residual gravity as input for the two-dimensional modeling program of Cady (1972). The relative linearity of the complete Bouguer anomaly gravity distribution allows realistic modeling in two dimensions. The dimension perpendicular to the direction of the gravity gradient is assumed infinite. In actuality, limitations are imposed on the model by obvious local variations in the CBA distribution of the north bay.

To model the relationship between the granite and sedimentary strata, certain assumptions must be made. First, a regional trend must be extracted from the data. The profile extends from the outcropping of granite near Santa Cruz to a well-determined depth to basement of 3,255 ft at Moss Landing (Martin, 1964). To establish a regional trend the transect was continued to the outcropping in the Gabilan Mountains. A regional trend of 1.3 mgal/n mile decreasing to the southeast was estimated. The removal of the regional trend from the CBA values along section A-A' leaves the residual gravity which should be directly related to the depth to basement (Fig. 7).

Next, a density contrast between the sedimentary strata and the basement complex must also be determined. The density of the granite was 2.73g/cm$^3$ as determined by Fairborn (1963), while the Monterey Formation has an average density of 1.80g/cm$^3$ as determined by Sieck

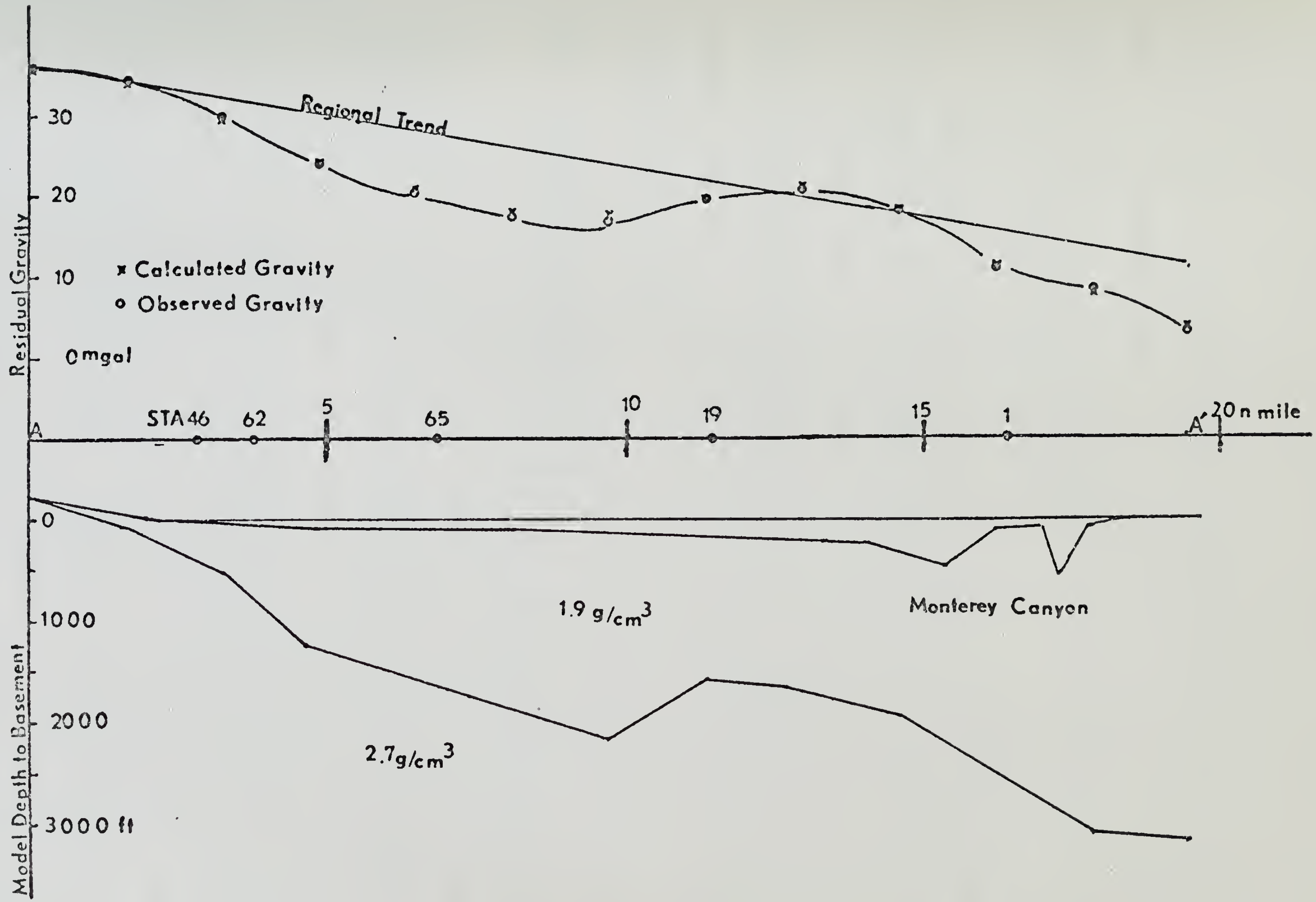



Fig. 7. [illegible] depth to basement profile A-A'.

(1964). The Purisma Formation of "poorly indurated gravels, sands, silts, and silty clay" (Greene, 1970) has been described as quite low in density with the exposed siltstone of the formation approaching the density of diatomite (Martin, 1964). An average density for the sedimentary unit of 1.9 g/cm$^3$ was assumed for modeling purposes and results in a density contrast of 0.8 gm/cm$^3$.

The profile itself (Fig. 7) is not a unique solution but does reflect a best fit of the data to the model with a tie-in to the granite at A and A'. The anomalous high in the interior of the survey area shows up as a definite break in the downward trending of the granite. The granite approaches the surface most closely at Station 19 where the sedimentary thickness is only of the order of 1500 ft.

## G. SOUTHERN MONTEREY TIE-IN

As previously mentioned, this survey was part of a joint survey of Monterey Bay. Brooks (1973) has reported a similar study of southern Monterey Bay. A tie-in of the two areas (Fig. 8) reveals an abrupt east to-west trending along the canyon axis of the predominantly north-south oriented near-shore isolines. Steep canyon wall gradients prevented a more direct tie-in of the two areas by gravimeter stations. It is possible that this anomalous feature demonstrates the existence of a Monterey Canyon fault near Moss Landing. Martin and Emery (1967) proposed a Monterey Canyon strike-slip fault 6 miles west of Moss Landing with left-lateral offset. Gravity evidence, on the other hand, points to right-lateral movement if a strike slip fault is assumed. An alternative and more

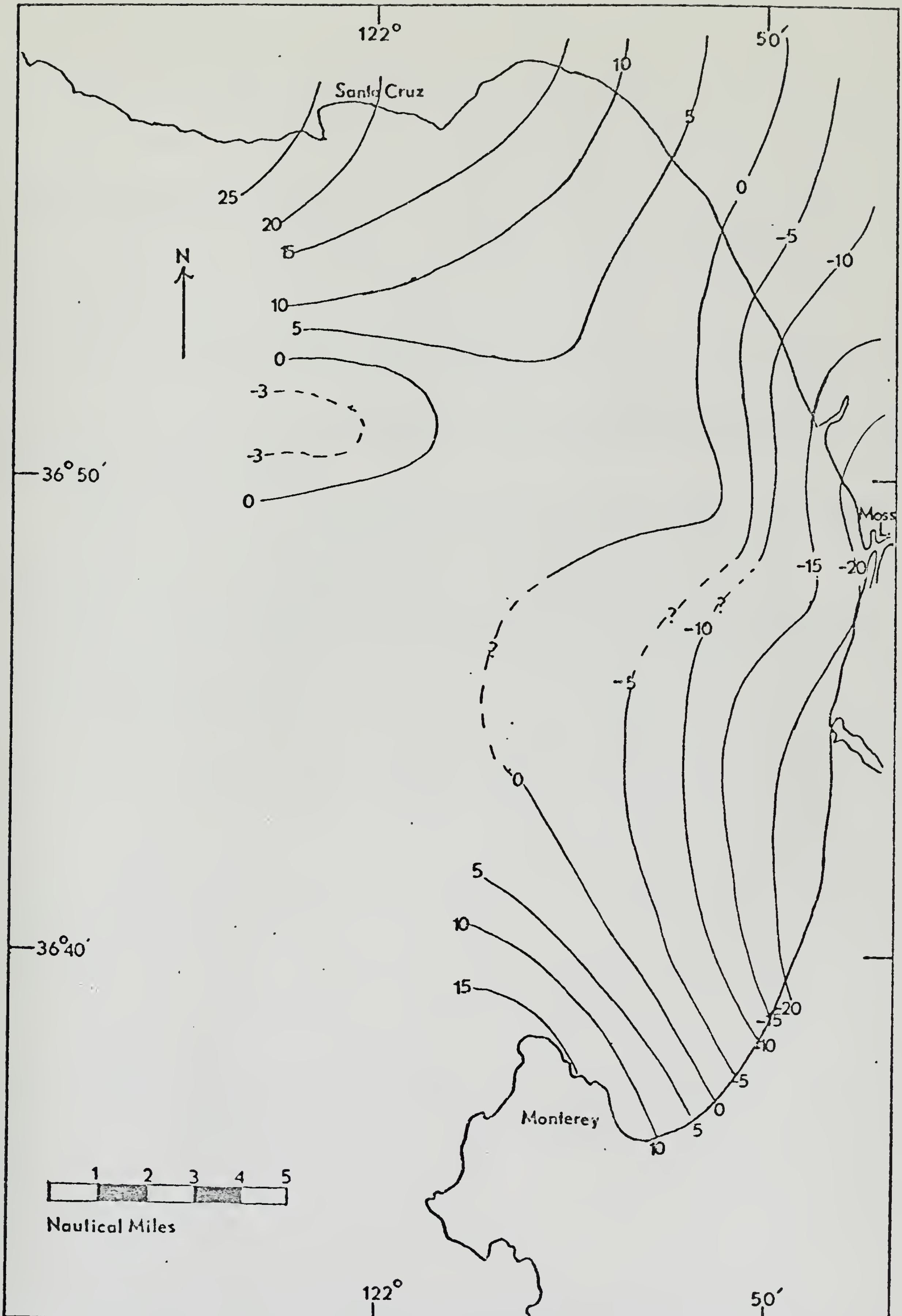



Fig. 8. Tie-in of northern and southern Monterey Bay
(southern Monterey Bay data from Brooks, 1973).

likely explanation is dip-slip faulting with down-dropping of the nearshore south bay. This contradicts Greene's (1970) tentative interpretation of the extended Monterey fault based on the 12 kJ seismic profiling of the north bay. Reduction and analysis of the 160 kJ data may prove helpful in resolving this conflict. West of Soquel Canyon it is felt that the north bay area is downdropped with respect to the south bay. Also to be considered is the fact that the contours may only be tracing the extension of the ridging to the southeast.

No other evidence of faulting in the survey area is noted. The possibility exists that one or more faults may lie within the area but that the density contrast and/or the fault displacement is insufficient to cause a noticeable indication in the distribution of the gravity isolines.

## V. FUTURE WORK

Since gravity data cannot provide a unique model of the subsurface structure of the survey area, it is felt that an analysis of magnetic data previously collected but unreduced be made to tie-in with the CBA distribution. Greene's publication of the seismic data in the future will do much to refine the present structural interpretation.

Sea surface gravity data across the canyon axis is available but as yet unreduced. Perhaps a stronger tie-in of the north and south bay may be made with sea surface values and the mass adjusted free air anomaly values.

Certainly an extension of the survey to the west is warranted in light of the interesting features evidenced. A survey in this area would do much to define the extent of the subsidence of the basement (the so-called Monterey Graben), and the possible transit of known faults to the west of this study area.

## COMPUTER PROGRAM

CBA COMPUTER PROGRAM FOR BOTTOM GRAVITY SURVEY

```
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION DEG(90),GBA(90),GTH(90),DW(90),DU(90),GOBS(9
     10),DEGR(90),GMG(90),GSTA(90),CC(90),TERC(90),ETID(90),
     1DWC(90),FAA(90),AMFAA(90),SBA(90),LAT(90),LATT(90),LON
     1G(90),LONGG(90),A(90),B90)
      CIRPI=3.14159
      DGDZ=0.09406
      READ (5,1) (DEG(I),I=1,80)
    1 FORMAT (8F10.7)
      READ (5,2) (DU(I),I=1,80)
    2 FORMAT (16F5.1)
      READ (5,3) (GOBS(I),I=1,80)
    3 FORMAT (8F10.2)
      READ (5,4) (DWC(I),I=1,80)
    4 FORMAT (8F10.2)
      READ (5,5) (CC(I),I=1,80)
    5 FORMAT (8F10.2)
      READ (5,6) (TERC(I),I=1,80)
    6 FORMAT (8F10.2)
      READ (5,77) (ETID(I),I=1,80)
   77 FORMAT (8F10.2)
      DO 10 I=1,80
      DW(I)=DU(I)-DWC(I)
      LAT(I)=36
   10 CONTINUE
      DO 15 I=1,27
      BASE=3323.11
      GSTA(I)=979891.7+((GOBS(I)-BASE)*1.039850)
   15 CONTINUE
      DO 27 I=28,49
      BASE=3324.87
      GSTA(I)=979891.7+((GOBS(I)-BASE)*1.039850)
   27 CONTINUE
      DO 28 I=50,80
      BASE=3324.64
      GSTA(I)=979891.7+((GOBS(I)-BASE)*1.039850)
   28 CONTINUE
      DO 30 I=1,80
      DEGR(I)=DEG(I)/57.295
   30 CONTINUE
      DO 40 I=1,80
      GTH(I)=978049.0*(1.0+(0.0052884*((DSIN(DEGR(I)))**2))-
     10.0000059*((DSIN(2.0*(DEGR(I))))**2))
   40 CONTINUE
      DO 50 I=1,80
      FAA(I)=GSTA(I)-GTH(I)-DGDZ*DW(I)
      AMFAA(I)=GSTA(I)-GTH(I)-DGDZ*DW(I)+(2.0*CIRPI*6.67*30.
     148*1.03*DU(I)/100000.0)+(2.0*CIRPI*6.67*30.48*1.03*DW(
     1I)/100000.0)
      SBA(I)=GSTA(I)-GTH(I)-DGDZ*DW(I)+(2.0*CIRPI*6.67*30.48
     1*2.67/100000.0)*DW(I)+(2.0*CIRPI*6.67*30.48*1.03/10000
     10.0)*DU(I)+ETID(I)
      GBA(I)=GSTA(I)-GTH(I)-DGDZ*DW(I)+(2.0*CIRPI*6.67*30.48
     1*2.67/100000.0)*DW(I)+(2.0*CIRPI*6.67*30.48*1.03/10000
     10.0)*DU(I)-CC(I)+TERC(I)+ETID(I)
   50 CONTINUE
 9999 STOP
      END
```

APPENDIX A

STATION RAW DATA AND CORRECTIONS

| STA | G OBSERVED | G THEORETICAL | TIDE | CC | TERC | ETID |
|---|---|---|---|---|---|---|
| 1 | 979897.511 | 979900.143 | -1.4 | 0.10 | 2.51 | -0.07 |
| 2 | 979911.237 | 979901.181 | -1.3 | 0.15 | 2.40 | -0.07 |
| 3 | 979913.836 | 979902.306 | -1.2 | 0.13 | 2.26 | -0.06 |
| 4 | 979912.901 | 979902.998 | -1.0 | 0.09 | 2.18 | -0.06 |
| 5 | 979911.653 | 979904.815 | -0.9 | 0.06 | 2.08 | -0.05 |
| 6 | 979912.381 | 979905.940 | -0.7 | 0.05 | 2.01 | -0.04 |
| 7 | 979913.109 | 979907.326 | -0.6 | 0.04 | 1.97 | -0.03 |
| 8 | 979915.199 | 979908.884 | -0.4 | 0.04 | 1.96 | -0.03 |
| 9 | 979917.486 | 979909.837 | -0.3 | 0.04 | 1.98 | -0.02 |
| 10 | 979922.062 | 979911.049 | -0.2 | 0.03 | 2.01 | -0.01 |
| 11 | 979926.429 | 979912.002 | -0.1 | 0.03 | 2.02 | 0.01 |
| 12 | 979928.925 | 979912.868 | 0.1 | 0.02 | 2.08 | 0.01 |
| 13 | 979927.573 | 979911.482 | 0.2 | 0.04 | 2.15 | 0.02 |
| 14 | 979925.389 | 979910.356 | 0.3 | 0.04 | 2.14 | 0.02 |
| 15 | 979921.334 | 979909.490 | 0.3 | 0.04 | 2.09 | 0.04 |
| 16 | 979916.769 | 979908.191 | 0.4 | 0.05 | 2.05 | 0.05 |
| 17 | 979915.729 | 979906.806 | 0.4 | 0.06 | 2.06 | 0.05 |
| 18 | 979916.051 | 979905.594 | 0.3 | 0.08 | 2.13 | 0.06 |
| 19 | 979916.987 | 979904.556 | 0.3 | 0.09 | 2.28 | 0.06 |
| 20 | 979915.427 | 979902.998 | 0.2 | 0.11 | 2.38 | 0.07 |
| 21 | 979912.932 | 979901.873 | 0.1 | 0.12 | 2.52 | 0.07 |
| 22 | 979909.188 | 979900.316 | 0.1 | 0.14 | 4.12 | 0.07 |
| 23 | 979912.828 | 979900.835 | 0.0 | 0.13 | 3.04 | 0.07 |
| 24 | 979911.372 | 979900.316 | 0.0 | 0.13 | 3.48 | 0.07 |
| 25 | 979912.100 | 979901.268 | 0.0 | 0.13 | 2.87 | 0.07 |
| 26 | 979911.268 | 979901.008 | -0.1 | 0.13 | 3.58 | 0.06 |
| 27 | 979911.798 | 979899.884 | 0.0 | 0.15 | 5.33 | 0.06 |
| 28 | 979882.620 | 979900.662 | 1.0 | 0.03 | 2.08 | 0.0 |
| 29 | 979883.130 | 979901.700 | 1.1 | 0.02 | 2.05 | 0.0 |

APPENDIX A (continued)

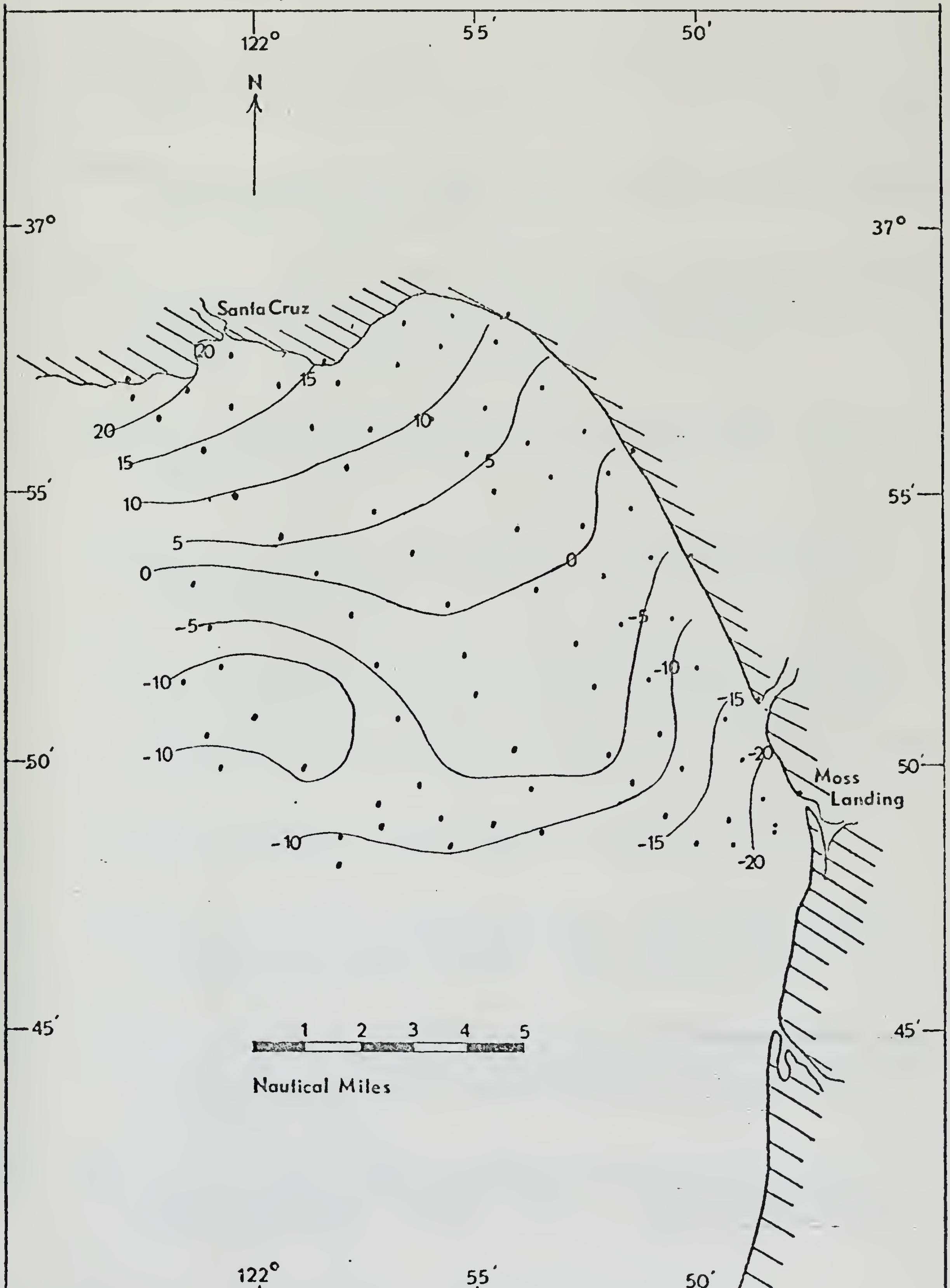
| STA | G OBSERVED | G THEORETICAL | TIDE | CC | TERC | ETID |
|---|---|---|---|---|---|---|
| 30 | 979887.299 | 979902.998 | 1.5 | 0.02 | 2.00 | -0.01 |
| 31 | 979891.979 | 979904.123 | 1.6 | 0.02 | 1.99 | -0.02 |
| 32 | 979895.317 | 979905.594 | 1.9 | 0.02 | 1.96 | -0.03 |
| 33 | 979900.204 | 979906.720 | 2.1 | 0.02 | 1.95 | -0.04 |
| 34 | 979905.934 | 979908.105 | 2.3 | 0.02 | 1.93 | -0.04 |
| 35 | 979909.365 | 979909.317 | 2.5 | 0.02 | 1.96 | -0.05 |
| 36 | 979912.495 | 979910.443 | 2.6 | 0.02 | 1.98 | -0.05 |
| 37 | 979915.303 | 979911.569 | 3.0 | 0.02 | 2.03 | -0.05 |
| 38 | 979918.838 | 979912.695 | 3.1 | 0.02 | 2.07 | -0.05 |
| 39 | 979922.280 | 979913.561 | 3.2 | 0.02 | 2.12 | -0.06 |
| 40 | 979927.999 | 979914.168 | 3.3 | 0.02 | 2.14 | -0.05 |
| 41 | 979929.569 | 979913.821 | 3.4 | 0.02 | 2.09 | -0.05 |
| 42 | 979929.580 | 979912.348 | 3.4 | 0.02 | 2.09 | -0.05 |
| 43 | 979931.140 | 979912.348 | 3.4 | 0.02 | 2.10 | -0.05 |
| 44 | 979934.155 | 979913.215 | 3.5 | 0.02 | 2.11 | -0.05 |
| 45 | 979935.299 | 979912.262 | 3.4 | 0.03 | 2.11 | -0.05 |
| 46 | 979940.405 | 979912.088 | 3.2 | 0.03 | 2.19 | -0.04 |
| 47 | 979883.046 | 979900.662 | 1.7 | 0.04 | 2.08 | -0.04 |
| 48 | 979891.469 | 979901.008 | 1.0 | 0.05 | 2.18 | -0.04 |
| 49 | 979891.584 | 979900.057 | 0.6 | 0.06 | 2.44 | -0.04 |
| 50 | 979897.771 | 979902.652 | 0.9 | 0.06 | 2.16 | 0.07 |
| 51 | 979903.074 | 979903.604 | 1.0 | 0.05 | 2.17 | 0.06 |
| 52 | 979903.906 | 979904.988 | 1.2 | 0.03 | 2.03 | 0.05 |
| 53 | 979906.297 | 979906.373 | 1.3 | 0.03 | 1.94 | 0.04 |
| 54 | 979910.353 | 979907.585 | 1.4 | 0.03 | 1.94 | 0.04 |
| 55 | 979913.472 | 979908.884 | 1.6 | 0.03 | 1.93 | 0.03 |
| 56 | 979915.136 | 979910.183 | 1.7 | 0.03 | 1.96 | 0.02 |
| 57 | 979917.840 | 979911.309 | 1.8 | 0.02 | 1.99 | 0.01 |
| 58 | 979922.519 | 979912.262 | 1.9 | 0.02 | 2.05 | 0.0 |
| 59 | 979926.575 | 979913.301 | 2.1 | 0.02 | 2.07 | -0.01 |
| 60 | 979928.654 | 979911.482 | 2.4 | 0.04 | 2.11 | -0.01 |
| 61 | 979932.190 | 979911.655 | 2.5 | 0.03 | 2.12 | -0.01 |

APPENDIX A (continued)

| STA | G OBSERVED | G THEORETICAL | TIDE | CC | TERC | ETID |
|---|---|---|---|---|---|---|
| 62 | 979934.997 | 979911.309 | 2.7 | 0.03 | 2.20 | -0.02 |
| 63 | 979930.734 | 979910.529 | 2.7 | 0.04 | 2.23 | -0.03 |
| 64 | 979927.094 | 979909.750 | 2.9 | 0.05 | 2.18 | -0.03 |
| 65 | 979922.831 | 979908.624 | 3.0 | 0.05 | 2.22 | -0.03 |
| 66 | 979918.360 | 979907.499 | 3.1 | 0.06 | 2.27 | -0.03 |
| 67 | 979915.760 | 979906.114 | 3.2 | 0.09 | 2.36 | -0.04 |
| 68 | 979920.221 | 979904.902 | 3.2 | 0.15 | 2.54 | -0.04 |
| 69 | 979924.692 | 979903.690 | 3.2 | 0.21 | 2.78 | -0.05 |
| 70 | 979914.918 | 979902.046 | 3.2 | 0.13 | 2.85 | -0.05 |
| 71 | 979912.422 | 979901.441 | 3.2 | 0.13 | 3.54 | -0.05 |
| 72 | 979910.862 | 979900.576 | 3.1 | 0.15 | 4.92 | -0.05 |
| 73 | 979915.542 | 979902.565 | 3.0 | 0.16 | 4.81 | -0.05 |
| 74 | 979910.966 | 979903.863 | 2.5 | 0.13 | 2.79 | -0.05 |
| 75 | 979910.031 | 979905.075 | 2.3 | 0.11 | 2.56 | -0.05 |
| 76 | 979912.422 | 979905.854 | 2.2 | 0.10 | 2.45 | -0.05 |
| 77 | 979917.933 | 979907.152 | 1.9 | 0.08 | 2.42 | -0.05 |
| 78 | 979910.550 | 979904.902 | 1.3 | 0.12 | 2.52 | -0.05 |
| 79 | 979911.486 | 979903.431 | 1.0 | 0.13 | 2.77 | -0.05 |
| 80 | 979913.556 | 979902.479 | 0.7 | 0.14 | 3.37 | -0.05 |
| A | 979876.448 | 979900.316 | -7.0 | 0.0 | 2.05 | 0.14 |
| B | 979884.340 | 979904.296 | -1.7 | 0.0 | 1.89 | 0.14 |
| C | 979900.375 | 979908.018 | -6.4 | 0.0 | 2.20 | 0.14 |
| D | 979909.439 | 979911.049 | -3.3 | 0.0 | 2.06 | 0.14 |
| E | 979921.214 | 979914.254 | -4.3 | 0.0 | 2.11 | 0.14 |
| F | 979928.153 | 979913.041 | -9.1 | 0.0 | 2.30 | 0.11 |
| G | 979939.520 | 979912.608 | -2.7 | 0.0 | 2.37 | 0.08 |

APPENDIX B

MASS-ADJUSTED FREE AIR ANOMALY DISTRIBUTION



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11. Dr. Howard Oliver 1
United States Geological Survey
345 Middlefield Road
Menlo Park, California 94025

12. Dr. S. L. Robbins 1
United States Geological Survey
345 Middlefield Road
Menlo Park, California 94025

13. Mr. H. Gary Greene 1
United States Geological Survey
345 Middlefield Road
Menlo Park, California 94025

14. Gravity Section 1
Naval Oceanographic Office
Washington, D. C. 20390

15. Mr. H. B. Parks 1
Lacoste and Romberg, Inc.
6606 North Lamar
Austin, Texas 78752

16. Professor Warren Thompson, Code 58Th 1
Department of Oceanography
Naval Postgraduate School
Monterey, California 93940

17. Master, R/V Acania 1
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13. ABSTRACT


Eighty underwater gravity measurements were made in northern Monterey Bay in water depths from 38 feet to 456 feet with a Lacoste and Romberg Model H underwater gravity meter. In addition, seven shoreline stations were occupied just above the swash zone with a Lacoste and Romberg Model G land gravity meter.

A complete Bouguer anomaly map was drawn and tied in with the previous land surveys and with one (a joint investigation) covering the southern half of the bay.

The isolines of the complete Bouguer anomaly indicate the relative vertical position of the basement complex Santa Lucia granite and the overlying sedimentary strata of the Purisma and Monterey Formations. Analysis gives evidence of a basement complex ridge in the north bay. A two-dimensional model of the depth to basement along a representative transect shows further evidence of the ridge. New evidence for an extended Monterey Canyon fault is presented.

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Gravity Survey | | | | | | |
| Gravity Isoline Analysis | | | | | | |
| Monterey Canyon | | | | | | |
| Northern Monterey Bay | | | | | | |